AD 731931

U. S. NAVAL SUBMARINE MEDICAL CENTER

Submarine Base, Groton, Conn.

REPORT NUMBER 648

NAVY DIVER/SWIMMER VOCABULARIES:
Phonemic Intelligibility in Hyperbaric Environments

by

Thomas Murry and Russell L. Sergeant
Naval Submarine Medical Center
and
Cynthia Angermeier
University of Connecticut

Bureau of Medicine and Surgery
Research Work Unit M4306.03-2020D.02

Released by:

J. E. Stark, CAPT MC USN
COMMANDING OFFICER
Naval Submarine Medical Center

30 December 1970

Approved for public release; distribution unlimited

21

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Submarine Medical Research Laboratory, NAVAL SUBMARINE MEDICAL CENTER	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

NAVY DIVER/SWIMMER VOCABULARIES: Phonemic Intelligibility in Hyperbaric Environments

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Interim Report

5. AUTHOR(S) (First name, middle initial, last name)

Thomas MURRY, Russell L. SERGEANT and Cynthia ANGERMEIER

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
30 December 1970	15	8

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) NSMRL Report Number 648
b. PROJECT NO. M4306.03-2020D	
c. ONR Contract # N00014-67-A-0197-0001	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Submarine Medical Center Box 600 Naval Submarine Base Groton, Connecticut 06340

13. ABSTRACT

Data from several investigations of speech intelligibility under various diving conditions were evaluated in an attempt to better understand the existing problems of communication under water and in chambers by Navy diving personnel. This paper compares data on the phonemic confusions found in diving environments with regard to their nature and severity and evaluates them in terms of the need to develop a new diving vocabulary. The data indicate that the sounds which are high in intelligibility in some environments are not in others. Moreover, the errors made at particular environments are not consistent over all conditions studied. From the point of view of maximum intelligibility of speech, the present analysis suggests that priority in the selection of words should be given to the specific phonemes that maintain their stability with increases in static pressure rather than to variations caused by the mixture of the breathing gas. Our survey of available data indicates that minor changes in the phonemic structure of messages may provide increased intelligibility in the hyperbaric chamber and underwater environments.

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Speech intelligibility						
Underwater communication						
Hyperbaric speech						
Phonemic analysis of speech						
Divers' speech						
Special vocabularies						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

UNCLASSIFIED
Security Classification

NAVY DIVER/SWIMMER VOCABULARIES:
Phonemic Intelligibility in Hyperbaric Environments

by

Thomas Murry and Russell L. Sergeant
Naval Submarine Medical Center
and
Cynthia Angermeier
University of Connecticut

NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY
U. S. NAVAL SUBMARINE MEDICAL CENTER REPORT NO. 648

Bureau of Medicine and Surgery, Navy Department
Research Work Unit M4306.03-2020D.02

Submitted by:

J. Donald Harris, Ph.D.
Head, Auditory Research Branch
Naval Submarine Medical Research Laboratory

Reviewed and Approved by:

Charles F. Gell

Charles F. Gell, M.D., D.Sc. (Med)
Scientific Director
NAVSUBMEDRSCHLAB

Reviewed and Approved by:

Joseph D Bloom

J. D. Bloom, CDR, MC, USN
Officer-in-Charge
NAVSUBMEDRSCHLAB

Approved and Released by:

J E Stark

J. E. STARK, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Center

SUMMARY PAGE

THE PROBLEM

To evaluate the nature and severity of speaking errors found in various diving environments.

FINDINGS

The data analyzed indicates that speech from hyperbaric chambers or underwater environments becomes distorted due to both the ambient pressure and the breathing mixtures. Minor changes in the phonemic structure of messages may increase intelligibility in these diving conditions. Additional improvement may also come from standardized message formats and special training for divers.

APPLICATION

The information in this review applies to the construction of special vocabularies for use by Navy divers in the water and in chambers. This review also provides a summary of the intelligibility studies done in various environments and an analysis which may be used to predict the types of errors in these environments.

ADMINISTRATIVE INFORMATION

This investigation was conducted as part of Bureau of Medicine and Surgery Research Work Unit M4306.03-2020D - Sensory Aids for Communication Under Water by Divers and Swimmers. It was approved for publication on 30 December 1970 and has been designated as NavSubMedRschLab Report Number 648. It is report No. 2 on the work unit.

The assistance of Miss Cynthia Angermeier was furnished under ONR Contract with the University of Connecticut (N00014-67-A-0197-0001).

PUBLISHED BY THE NAVAL SUBMARINE MEDICAL CENTER

ABSTRACT

Data from several investigations of speech intelligibility under various diving conditions were evaluated in an attempt to better understand the existing problems of communication underwater and in chambers as encountered by Navy diving personnel. This paper compares data on the phonemic confusions found in diving environments with regard to their nature and severity and evaluates them in terms of the need to develop a new diving vocabulary. The data indicate that the sounds which are high in intelligibility in some environments are not so in others. Moreover, the errors made in particular environments are not consistent over all the conditions studied. From the point of view of maximum intelligibility of speech, the present analysis suggests that priority in the selection of words should be given to the specific phonemes* that maintain their stability with increases in static pressure rather than to variations caused by the mixture of the breathing gas. Our survey of available data indicates that minor changes in the phonemic structure of messages may provide increased intelligibility in the hyperbaric chamber and underwater environments.

*Phonemes – smallest unit of speech that distinguishes one utterance from another.

BLANK PAGE

NAVY DIVER/SWIMMER VOCABULARIES:
Phonemic Intelligibility in Hyperbaric Environments

INTRODUCTION

Recent interest in diver communication problems has resulted in a rather extensive research program by both Navy and civilian scientists. The results of the programs in communication research indicate that divers' speech becomes markedly reduced in intelligibility as a result of the high ambient pressure and/or the exotic gas mixture which the diver must breathe. While the research has shown that generally, there is a loss in intelligibility of speech in helium-oxygen mixtures (Sergeant, 1963[1]; Cooke and Beard, 1965[2]; Hollien and Thompson, 1967[3]), only Sergeant[4] and Murry[5]* have analyzed the divers' speech to determine the specific phonemic errors, the patterns of phonemic confusion and the relationship of these to phonemic responses made in more general speaking conditions (i.e., in air at normal atmospheric pressure). Sergeant's results suggest that the errors made in speech spoken in helium-oxygen mixtures are similar to those made in air; however, in his study only 13 consonants were analyzed and the speech was restricted to samples taken at one atmosphere (ata) of pressure. While Murry's[5] results include more consonants, his data also was obtained at only one depth. The results of both studies imply that the errors made by the listeners, instead of being random, seem to resemble perceptual confusion patterns which had been found for speech in air (Miller and Nicely, 1955[6]).

Since Sergeant's initial report of phonemic confusions in 1967 and Murry's later report, other phonemic data obtained during intelligibility testing of divers' speech has now become available. With this additional data, a more complete comparison of errors made at different depths and different breathing mixtures is now possible.

Although the several experiments referred to above were undertaken independently, they pertain to the same topic, i.e., analysis of phonemic intelligibility of speech produced within conditions of high ambient pressure and/or helium-rich mixtures. In order to better understand the patterns of errors made in various diving environments, it is appropriate that these independent studies be collated into a unitary set of data, and then related specifically to existing problems of communication among Navy diving personnel.

PURPOSE

This paper compares data from several studies with regard to the severity and nature of phonemic confusions found in diving environments. In addition, errors are evaluated in terms of the need to develop new diver speaking patterns and/or new diver vocabularies for use by Navy personnel working under

The phonemic analysis data reported by Murry in 1969 was taken from intelligibility test data reported by Hollien and Thompson, November, 1967, Acoustical Society of America, Miami, Florida.

high ambient pressures and breathing a mixture of helium-oxygen.

BACKGROUND

This report compares data from studies reported by Miller and Nicely[6], Sergeant[4], Murry[5], and Sergeant[7]. While the specific testing methods used to obtain the data differed, the combined results are extensions of standard intelligibility testing procedures. In the four studies from which the data were compiled, intelligibility tests were carried out using various numbers of speakers and listeners. Test conditions for the speakers are reported below; the listeners for all studies were listening in standard listening environments, and they heard the stimuli through earphones or a high quality loudspeaker system. Responses by listeners were used to construct phonemic response matrices which showed correct responses along one of the diagonals, and error responses, or confusions, throughout the remaining cells of the matrix. The several studies were conducted under varying test conditions and are summarized in Table 1.

Table 1 lists the different studies, conditions of pressure and gas mixture, and specific phonemes considered in the present report. The Hollien-Thompson data reported by Murry[5] is based on the

Table 1. Studies from which the summary data in this report were obtained

Investigations	Test Conditions	Phonemes Analyzed
Miller-Nicely[6] *	Air 0'	(16) p t k f θ s ʃ b d g v ð z ʒ m n
Sergeant[4] **	HeO_2 0'	(13) f s p t k b d g m n r l w
Murry[5] ***	HeO_2 200'	(23) p b m t d n f v θ ð s z ʃ tʃ l w r k g h ŋ dʒ j
Sergeant[7]	Air 250'	(20) z v ð f s θ ʃ b d g p t k tʃ m n ŋ r l w

* 0 dB speech to noise level

** 1 dB speech to noise level

*** This data was derived from intelligibility tests carried out by Hollien and Thompson.[3]

phonemic confusions for 23 standard English consonants, while the other studies used subsets of this group of phonemes. The data from all of the studies seemed adequate to transform the raw scores into weighted percentage error scores; this permits convenient comparisons to be made of intelligibility under changes of pressure and gas mixture. However, it should be pointed out that data from Sergeant's study of compressed air employed a 6-item forced choice answer sheet. This restricted greatly the possible alternatives which the listener could make. In certain instances, the expected most frequent error response to a phoneme was not one of the 6 possible alternatives for the listener to choose. Consequently, care must be used in relating data of this sort with regard to the confusions made. On the other hand, it would not be expected that the overall phonemic percent correct intelligibility of a particular sound would not be greatly effected by the forced choice aspect. In the three other studies, responses were always open-ended. The listeners were instructed to write the word they thought they heard, and that response was used to determine if the specific phoneme in question was heard correctly.

EVALUATION OF SPECIFIC PHONEMIC INTELLIGIBILITY

The specific phonemic intelligibility of a sound is defined as the percentage of times that the correct response is made out of the total number of times which the sound was actually the stimulus. This percentage indicates the probability that the sound in question will be correctly recognized when presented.

Table 2 presents the data of the four studies evaluated in this report in terms of the specific intelligibility of each sound. Each sound is ranked for each gas mix/pressure condition according to its percent correct responses of the total number of times it was used as the stimulus. From the table it can be seen that [m] is easily recognized in air and in helium-oxygen mixtures under standard atmospheric pressure. However, when pressure increases, such as is the case at a depth of 200 feet, the [m] sound becomes one of the least intelligible sounds. Therefore, it might be suggested that when choosing words for special vocabularies, those words containing the [m] sound would be more desirable for shallow depths since the intelligibility of the [m] decreases under high ambient pressures. Thus, [m] words would be a hindrance to communicability for the Navy deep sea diver. In a similar manner, Table 2 can be used to evaluate the effectiveness of other phonemes with regard to their intelligibility in special vocabularies for use by Navy personnel. However, caution must be used since the intelligibility values in Table 2 may not apply to all combinations of phonemes, especially words having consonantal blends.

Table 3 is a correlation matrix for four speaking conditions. The coefficients were obtained from the rankings of specific phonemic intelligibility. The most surprising aspect of the matrix is that none of the coefficients were significant (.05 level). We conclude that one cannot predict the specific phonemic

Table 2. Specific phonemic intelligibility and its rank order for each of four environmental conditions. Specific phonemic intelligibility is the percent correct for each phoneme based on the number of presentations of the particular phoneme. The higher percentages indicate the more easily recognized sounds.

AIR						HeO_2					
0'			250'			0'			200'		
R	Stim	%	R	Stim	%	R	Stim	%	R	Stim	%
1	ʃ*	97	1	ð	98	1	l	90	1	h*	87
2	m*	97	2	w	96	2	m	78	2	r*	87
3	n	95	3	tʃ	95	3	b	75	3	ŋ	81
4	ʒ	92	4	ʃ	94	4	g	73	4	j	80
5	θ	86	5	r	91	5	n	61	5	s*	79
6	t	79	6	ŋ*	89	6	p	59	6	n*	79
7	d*	76	7	v*	89	7.5	r	55	7	z	78
8	f*	76	8	θ	88	7.5	d	55	8	t*	75
9	b*	75	9	s	83	9.5	k	49	9	k*	75
10	v*	75	10	g*	82	9.5	t	49	10	l	71
11	s*	75	11	d*	82	11.5	f	48	11	p*	68
12.5	g	60	12	l	79	11.5	w	48	12	b*	68
12.5	z	60	13	f	78	13	s	28	13	dʒ	66
14	k	52	14	z	71				14	d	61
15	ð	51	15	b	69				15	ʃ	60
16	p	50	16	p	66				16	m	57
			17	t	63				17	v	56
			18	n	57				18	f	54
			19	m	54				19	ð	50
			20	k	44				20	tʃ	47
									21	g	43
									22	θ	42
									23	w	32

*The rank order for this sound was determined prior to rounding off to the nearest percent correct shown.

Table 3. Correlation matrix of specific phonemic intelligibility (percent correct) for different environmental conditions. The coefficients are rank order correlations.

		AIR		HeO_2	
		0'	250'	0'	200'
AIR	0'	-----	-.07(N=15)	+.23(N=10)	-.08(N=15)
	250'		-----	-.32(N=13)	-.32(N=20)
HeO_2	0'			-----	-.08(N=13)
	200'				-----

intelligibilities from the data of one condition of gas/pressure; rather additional conditions are needed for such prediction.

PHONEMIC CONFUSION MATRICES

A phonemic confusion matrix (See Appendix I) was constructed for each of the four studies listed in Table 1. An entry in these matrices is the percentage of all of the incorrect responses made to a specific stimulus which was due to a particular phoneme. For example, for Sergeant's data at 250 feet in air, the entry in the Appendix, for the stimulus [k] and response [t] is 22. This means that [t] accounted for 22 percent of all the errors made to the stimulus [k]. The entries of error percents in Appendix I provided the basis for the remaining analysis and evaluation reported herein.

The matrices in the appendix show that the dispersion of the error responses increased as pressure increased. In general, the sounds which require the vibration of the vocal cords termed, "voiced sounds" (b, d, g, v, ð, z, ʒ, j, dʒ, l, r), were substituted for each other. For example, [g] was often substituted for [b]. Those sounds which do not require vibration of the vocal cords termed "non-voiced" sounds (p, t, k, f, θ, s, ʃ, tʃ, h) were likewise used as substitutions for other "non-voiced" sounds. An example of this type found in the matrices is the [p] substituted for [t]. One condition, however, shows a different pattern from the other three examined in this paper. For subjects breathing air at 250 feet, a large number of the non-voiced sounds, particularly the [p], [t], and [k] and the nasal sounds [m] and [n], were used as substitutions for the [b], [d], and [g] voiced sounds. One further point of importance, regardless of the speaking condition, the largest percent of errors occurred with the non-voiced and nasal phonemes.

An interesting as well as useful piece of information about a phoneme relates to its tendency to be selected as the confused sound once an error has been made. These scores, referred to as confusability scores, were determined by adding the percents listed in each column of the tables; in Appendix I. These confusability scores along with the rank order of confusability for each phoneme according to the four environmental conditions of gas/pressure, are shown in Table 4. This table can be used to determine which sounds appear most often, or least often, once an error is made. Thus, to construct a vocabulary to be used in helium environments, one should consider not only the degree of intelligibility of a sound, but also the frequency with which the sound is used erroneously, i.e., its confusability.

Table 5 presents the rank order correlations for the phonemic confusability between the air/helium-oxygen conditions in normal and pressurized environments. It may be important to note the statistically significant (.05 level) negative correlation between air at 250 feet and helium at sea level 0 feet. The sounds showing high confusability in air at 250 feet apparently become low in confusability for the 0 feet helium-oxygen condition. The other significant correlation was a positive one between the two conditions of pressure. The effect of speaking within atmospheres of high ambient pressure alone seems to alter the degree of confusability among phonemes in such a way that the same sounds are high or low in confusability regardless of the gas mixture being breathed. This fact would appear to be important in the design of efficient vocabularies for use by Navy divers. From the point of view of maximum intelligibility of speech, these analyses suggest that priority during selection of words for vocabularies should be given to the specific factors of phonemes that are associated with increases in static pressure rather than to variations caused by the mixture of gas being breathed.

COMMENT ON HELIUM

Previous studies have reported on the poor intelligibility levels of helium speech (Sergeant, 1963[1] ; Hollien and Thompson, 1967[3]); however, the consistency of the error responses across the several speaking conditions surveyed in this report appears to be somewhat surprising. Sergeant[4] reported consistent errors in helium and in air at one atmosphere; this survey indicates that these consistencies are maintained to some extent at 200 feet in a helium-oxygen mixture. This is not to imply that responses to speech in air and in a helium mixture are entirely alike; on the contrary, the variability of the errors to certain sounds in helium would not be predicted from the results obtained in air mixtures alone. For example, in air, the fricatives [f, v, θ, ð, s, z, ʃ, dʒ] are almost exclusively the most common substitution to a fricative stimulus; in helium, fricatives as well as the glides [r, l, m, n, j] are found to be the most common substitution to fricatives. The

Table 4. Confusability scores for each phoneme and its rank order for each of four environmental conditions. Confusability scores were determined by adding the percents listed in each column of Appendix I. The score is an indication of the tendency of sound to be the error sound, once an error is made. The higher the score, the more often this sound was used as an incorrect response.

AIR						HeO_2					
0'			250'			0'			200'		
R	Stim	C.S.*	R	Stim	C.S.*	R	Stim	C.S.*	R	Stim	C.S.*
1	θ	160	1	k	262	1	l	172	1	l	222
2	k	153	2	n	247	2	t	162	2	n	181
3	ð	145	3	p	175	3	r	151	3	t	172
4	p	128	4	t	164	4	p	120	4	s	152
5	g	127	5	f	160	5	b	107	5	f	138
6	v	121	6	m	138	6	k	103	6	r	110
7.5	f	105	7	h	117	7	d	72	7	h	106
7.5	t	105	8	l	86	8	f	68	8	k	100
9	d	102	9	g	79	9	n	66	9.5	ð	84
10	z	97	10	s	65	10	m	56	9.5	j	84
11	n	93	11	d	52	11	g	44	11	d	82
12	ʒ	76	12	r	48	12	s	39	12	m	80
13	m	69	13	z	42	13	w	26	13	v	61
14	b	55	14	θ	29	14	j	13	14	p	56
15	s	47	15.5	v	27				15	b	47
16	ʃ	18	15.5	ʒ	27				16	w	41
			17	dʒ	26				17	θ	30
			18	ʃ	22				18	g	29
			19	w	13				19	z	24
			20.5	ð	7				20	ʃ	18
			20.5	tʃ	7				21	ʒ	11
									22	tʃ	10
									23	dʒ	3

Table 5. Correlation matrix of specific phonemic confusability (error responses) for four different environmental conditions. The coefficients are rank order correlations.

		AIR		HeO_2	
		0'	250'	0'	200'
AIR	0'	-----	+.07(N=15)	+.44(N=10)	+.02(N=15)
	250'		-----	-.84*(N=10)	+.63*(N=21)
HeO_2	0'			-----	+.39(N=14)
	200'				-----

*Significant at .05 level if N=10 and r >.56, N=14 and r >.47, N=15 and r>.45, or N=21 and r>.35.

degree of consistency for the phonemic error substitution noted across the particular environments represented in the data would tend to suggest that at least at the phonemic level, little change is required in a vocabulary to combat the effects of helium. Rather, the majority of the effort should be concentrated on overcoming the overall relatively low intelligibility of speech found under helium conditions. Based on available data, there does not appear to be a need to develop special words from contrived phonemic patterns if gas mixture alone is the point of consideration.

CONSIDERATIONS IN CONSTRUCTING A DIVER/ SWIMMER VOCABULARY

The phonemic considerations outlined above are only one aspect in the specification of what is the best vocabulary for use by Navy divers. In addition to the actual construction of a vocabulary for divers, a format for the speaker to follow is necessary. This enables the listener to be at least partially prepared for what is coming and thereby make use of the inherent redundancy of message sets (Shannon and Weaver, 1949[8]). The speaker/listeners format should include the following items:

(1) Caller's tag or name.
(2) Receiver's tag or name.
(3) Position information.
(4) Present condition.
(5) Specific message.

The caller's tag or name may be number or color coded, that is, diver one, diver two or blue diver, white diver, etc. It is important to note that phonemic considerations would appear to rule out the use of many colors. For example, the words orange, yellow, and even red, when inserted into the phrase "red diver", contain many of the phonemes which have been found to have either a low intelligibility or a high level of error dispersion.

In the jargon of Navy divers, the receiver's tag is often given as "topside" or "surface". Also since there is usually just one "topside" unit, it need not have any special tag. However, it is helpful when reporting to surface support personnel for the diver to use the receiver's tag to gain attention.

Position information should include depth and estimated distance from other divers or from the habitation. It may not always be possible to give position information nor may time allow for such information to be given. Nonetheless, if the diver is in need of assistance, he must be able to guide or direct another diver to his location. Thus, the depth, the distance, and direction from the starting point would appear to be important.

Information not only of the diver's position but also of the conditions below the surface may also be important. Such information can provide necessary help which the diver requires. Therefore, the diver should report in a given order: (A) Air supply information, (B) Temperature, (C) Imminent dangers - animals, sickness, equipment problems. In some emergency situations, it will be necessary to get a support diver and equipment to the diver in trouble. In other cases, the diver may just require a simple decision to surface or to dive deeper.

In general, the message format outlined above will be all that is required in an emergency conversation. However, there may be general information to be passed from one group to another. The format would remain the same and then, in addition, the diver and surface crew would carry on a conversation such as might be necessary in the case of equipment repair.

Once a format is adopted, and its phonemic organization can be evaluated, it becomes imperative that transmission of the message contain as little distortion as possible. Distortion may result from faulty equipment or poor speaking habits. It is not the purpose of this paper to evaluate unscramblers; however, regardless of the type of equipment used to send the messages, some consideration must be given to the speaker. Previous studies (See summary of research program in voice communication in Speech Monographs, Vol XIII, 1946, 1-69) have indicated the importance of a training program aimed at getting speakers to speak louder, slower, and with particular emphasis at certain points of the message. Such programs have been shown to significantly increase intelligibility after one hour of training.

CONCLUSIONS

The available data indicates the speech from chamber or underwater environments becomes distorted due to changes in ambient pressure and breathing mixtures. The nature of these distortions is somewhat similar regardless of the gas mixture, that is, intelligibility studies in air serve to partially predict the sounds which may be in error when helium mixtures are breathed. On the other hand, the kinds of errors are not so independent of aspects of the environment, particularly in conditions where the ambient pressure is great. Our survey of available data indicates that minor changes in the phonemic structure of messages may provide increased intelligibility in hyperbaric chamber and underwater environments. Additional improvement of communication by Navy personnel can be achieved through the use of a standard communication format and speaker training. Finally, the detailed information presented in this report is important to construction of special vocabularies for use by Navy personnel who must operate under hyperbaric conditions.

REFERENCES

1. Sergeant, R.L., Speech during respiration of a mixture of helium and oxygen. Aerospace Med., 1963, 34, 826-829.

2. Cooke, J. and Beard, S., Verbal communication intelligibility in oxygen-helium and other breathing mixtures at low atmospheric pressures. Aerospace Med., 1965, 36, 1167-1172.

3. Hollien, H. and Thompson, C., Speech intelligibility as a function of helium-oxygen breathing mixture and ambient pressure. J. Acoust. Soc. Am. 1967, 42, 1199 (A).

4. Sergeant, R.L., Phonemic analysis of consonants in helium speech. J. Acoust. Soc. Am. 1967, 41, 66-69.

5. Murry T. A method for analyzing phonemic errors in underwater speech intelligibility testing. CSL/ONR Progress Report No. 24, 1969, 1-12.

6. Miller, G. A. and Nicely, P., An analysis of perceptual confusions among English consonants. J. Acoust. Soc. Am. 1955, 27, 338-352.

7. Sergeant, R. L., Intelligibility of speech produced in compressed air. J. Acoust. Soc. Am. 1970, 47, 128 (A).

8. Shannon, C. E. and Weaver, W., The Mathematical Theory of Communication. Urbana: University of Illinois Press, 1949.

APPENDIX

Appendix I. Appendix I contains the phonemic confusion matrices for four environmental conditions. In each matrix, sounds in the column on the left are the stimuli and the sounds listed across the top row are the responses. Each cell entry is the percent of all the errors made to the sound listed to its left. The total of all the percents across any one row should equal 100 percent of the errors made for the specific stimulus for that row.

0' HeO_2 SERGEANT

																										TOTALS OF ROWS	
	p	t	k	f	θ	s	ʃ	tʃ	dʒ	b	d	g	v	ð	z	ʒ	m	n	ŋ	r	l	w	j	h	OMIT	PERCENT	NUMBER
p	X	34	28	14						3	3									3	7				7	99	29
t	36	X	36	5		3				7	2									2	7		2		4	102	61
k	41	35	X	11		7				2	2														2	100	46
f	6	36	22	X		20				6	2						2				2				4	100	50
θ*					X												1										
s	25	21	6	15		X				10	4	4									3	1			9	99	68
ʃ*							X																				
tʃ*								X																			
dʒ*									X																		
b		9	4	13		4				X	30	4									9				26	99	23
d		8	3	8						24	X	34								5	8		8		3	101	38
g	7	4	4							26	22	X					7	4	4		4						
v*													X														
ð*														X													
z*															X												
ʒ*																X											
m		10								5							X	55		5	25					100	20
n		3				3				10	3						46	X		5	10	8	3		10	101	39
ŋ*																			X								
r	5			2						2	2	2							5	X	64	17				99	42
l										10										70	X				20	100	101
w		2				2				2	2								2	57	30	X			2	99	46
j*																							X				
h*																								X			
TOTAL	120	162	103	68	-	39	-	-	-	107	72	44	-	-	-	-	56	66	-	151	172	26	13	-	100	1299	499

*Not used as a stimulus

250' AIR SERGEANT

	p	t	k	f	θ	s	ʃ	tʃ	dʒ	b	d	g	v	ð	z	ʒ	m	n	ŋ	r	l	w	j	h	OMIT	TOTALS OF ROWS PERCENT	TOTALS OF ROWS NUMBER
p	X	15	15	10						3	26			3			3	3		3	3	5		13	0	102	39
t	26	X	33	4	7	4		1		4	3						4	7		1		1		1	5	101	137
k	9	22	X	30	2		9	4			2	7					2		4					9	0	100	46
f	39	14	11	X		11	4			7		4												7	4	101	28
θ	29	50	7		X	7															7				0	100	28
s	2	14	15	3	20	X		2			7		3		12			2				2		7	12	101	59
ʃ							X																				1
tʃ			50					X							20		25				5					100	20
dʒ									X									36			5				59	100	22
b	1	10	1	3		1			6	X	1	6	3				24	3	6	8	15			3	9	100	114
d	2	4		9		2				7	X	12	4				6	42	4			9				101	101
g	21	8	4	4		4				8	2	X					17	8	13	8	2					99	48
v	5		10			10							X		10		5	15							45	100	20
ð	8		80								4			X			4	4								100	25
z			4			4	9								X	17									65	99	23
ʒ																X											
m				16		4				14			10				X	35			14			6		99	49
n		1	6	16		9				4	7	10	11				23	X		3	7	1			1	99	70
ŋ										8								92	X							100	12
r				20					20	20		20								X	20					100	5
l	63									25		12									X					100	8
w		17	17							17		8						8		25	8	X				100	12
j																							X				
h	27	9	9	45		9																		X		99	22
TOTAL	175	164	262	160	29	65	22	7	26	117	52	79	27	7	42	-	138	247	27	48	86	13	-	46	200	2101	367

0 AIR MILLER AND NICELY

	p	t	k	f	θ	s	ʃ	tʃ	dʒ	b	d	g	v	ð	z	ʒ	m	n	℘	r	l	w	j	h	OMIT	TOTALS OF ROWS PERCENT	TOTALS OF ROWS NUMBER
p	x	26	60	5	9														1							100	146
t	51	x	47	2																						100	59
k	62	33	x	3	1		1											1								101	138
f	6	5	8	x	71	6				2				2			2									102	65
θ	9	5	3	72	x	8							2													99	118
s		3	2	9	66	x	17					3														100	58
ʃ		33	33			33	x																			99	9
tʃ								x																		-	-
dʒ									x																	-	-
b				9	5					x	5		44	35	1											99	77
d											x	68		6	11	15										100	71
g											67	x		4	7	23										101	111
v				5	2					32		3	x	49	7	2										100	59
ð										7		10	65	x	18											1001	99
z											18	25	4	24	x	28										99	92
ʒ					6						12	18	6		53	x		6								101	17
m										14							x	86								100	7
n														25		8	67	x								100	12
℘																			x							-	-
r																				x						-	-
l																					x					-	-
w																						x				-	-
j																							x			-	-
h																								x		-	-
TOTAL	128	105	153	105	160	47	18	-	-	55	102	127	121	145	97	76	69	93	-	-	-	-	-	-		1601	1138

200′ HeO_2 MURRY

	p	t	k	f	θ	s	ʃ	tʃ	dʒ	b	d	g	v	ð	z	ʒ	m	n	ŋ	r	l	w	j	h	OMIT	TOTALS OF ROWS	
																										PERCENT	NUMBER
p	X	50	7	18														2						7	16	100	44
t	13	X	56	1		1				1		1												15	10	98	215
k	11	59	X	3		2		4		1		1						1		1	1			7	9	100	138
f	20	5	3	X	20	11	1	1		6	1		3	1	1						1			12	14	101	117
θ		5		38	X					3	5			21				3						13	13	101	39
s	2	12	4	35	6	X	9	2						2	5					1		1		5	15	99	98
ʃ				8		72	X																4	16		100	25
tʃ	1	18	47	2	1	13	8	X																7	3	100	88
dʒ			2	4					X		5	2		7						2	2	5	43	9	20	101	56
b	2			5						X	11	1	2	7			5	8			41	1	1	6	10	100	88
d						1			1	13	X	15		12	1		4	20			11		1	1	19	99	279
g				2						2	26	X		22			2	12			5	9	18		3	101	65
v	1	3		1		11		3		2	11	2	X	1	9		6	8		12	3				28	101	185
ð					1					6	4	3	4	X	4		7	13		4	22	3	3	6	19	99	179
z		5		6		23			2		3	1	19		X										41	100	80
ʒ																X											
m											2		1	2			X	63		18	1	4			10	101	200
n				1							3		4	3	1		19	X	8	36	3	4			18	101	272
ŋ											5		9				18	18	X		14				36	100	22
r		9				2					4		10		2		1	12	1	X	14	1	1	1	41	99	92
l		2		3	1	1							9	2	1		9	6	2	31	X	2	2	1	31	103	182
w				2	1					2				1			3	3		51	20	X			17	100	180
j		1								2	2						4	6		7	31	13	X	1	32	99	84
h	6	3	11	9		15				9		2		3			2	6			3	2	2	X	28	101	56
TOTAL	56	172	100	138	30	152	18	10	3	47	82	29	61	84	24	-	80	181	11	110	222	41	84	106	433	2304	2784